# EN200

# LAB #5/6 PRELAB

# RIGHTING ARM - VERTICAL/TRANSVERSE SHIFTS IN G

Instructions

1. The first part of this lab consists of a prelab that covers the theory that will be examined experimentally in this lab.

2. It is to be handed to your instructor at the beginning of the lab period.

3. If you can, answer the questions without referring to your notes. Only refer to them when you are confused or fail to understand a concept. This will greatly improve your understanding of the concepts the lab is designed to reinforce. Remember you will have no notes during quizzes, tests and exams.

4. By conscientiously completing this prelab, you will have a thorough understanding of what the lab is trying to show. Your lab performance will be maximized.

5. **All work must be shown on your lab for proper credit**. This means that you must show generalized equations, substitution of numbers, units and final answers. Engineering is communication. Work that is neat and shows logical progression is easier to grade.

**Student Information**

Name: ___________________________

Section: __________

Date: ____________

**Aim:**

- Reinforce the students' understanding of righting arm theory.
- Demonstrate and predict the effect that an increase in KG has on stability.
- Demonstrate and predictthe effect of a transverse shift in the center of gravity on ship stability.

**Part 1:Prelab**

**Apparatus:**

1. The stern view of this apparatus is shown in Figure 1. A 27-B-1 model in its normally loaded condition is floated so that steel pins mounted on its bow and stern fit into vertical guides on the side of the tank. These pins hold the model in the center of the tank while allowing it to float freely in the vertical direction. The transverse center of gravity of the model will be shifted by moving weights to the starboard post.

2. The model has a circular disc mounted on its stern which has a wire connected to its underside. The wire runs in a channel around the perimeter of the disc and then passes to a force gauge mounted on the side of the tank. The gauge can be moved transversely using a worm drive mechanism to apply a force in the wire ($F_{wire}$). The magnitude of $F_{wire}$ can be measured on the gauge.

3. A protractor incorporating a line and weight is mounted on the deck and used to monitor the angle of heel ($\phi$).

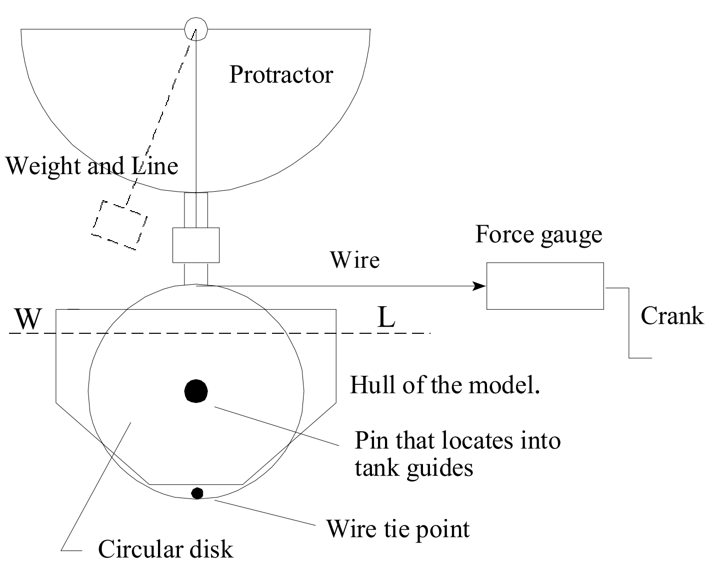


Figure 1 - Stern view of apparatus

**Theory**

4. The 27-B-1 model is going to be heeled by the presence of an external force, in this case the force in the wire ($F_{wire}$). This force ($F_{wire}$) is actually part of a couple, its equal and opposite partner being the force on the pin preventing the model from translating in the tank ($F_{pin}$).

5. You will recall that a couple is a particular type of moment defined as:

   *".... a pair of equal and opposite forces separated by a distance"*

   a. What is the effect of a couple on a body? ______________________________

   b. What are the units of a couple? _______________________________________

6. When the 27-B-1 is heeled to a particular angle by $F_{wire}$ you will find that it remains at that heel without further rotation or translation. Is the model in static equilibrium?

   Why? ___________________________________________________________________

   ________________________________________________________________________

7. In the box below show how the conditions for static equilibrium can be expressed mathematically.

| |
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8. Figure 2 is a simplified diagram of the 27-B-1 model heeling in the tank.

   a. On the figure show the location and direction of the 2 forces $F_{wire}$ and $F_{pin}$ .

   b. In the box below give the equation for the magnitude of the external couple created by these forces in terms of the quantities on the Figure.

| |
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9. Since the model is in static equilibrium at each angle of heel, there must be an equal and opposite couple being created by the model. This couple is being created by the 2 resultant forces due to the model's displacement ($\Delta_S$) and its buoyant force ($F_B$).

   a. On the figure show the location and direction of the 2 forces $\Delta_S$ and $F_B$.

   b. Show the righting arm between these 2 forces. Call this distance GZ.

   c. In the box below give the equation for the magnitude of the internal couple created by these forces in terms of the quantities on the Figure.

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10. Assuming the model is at static equilibrium, derive the equation that links the 2 couples in the boxes above.

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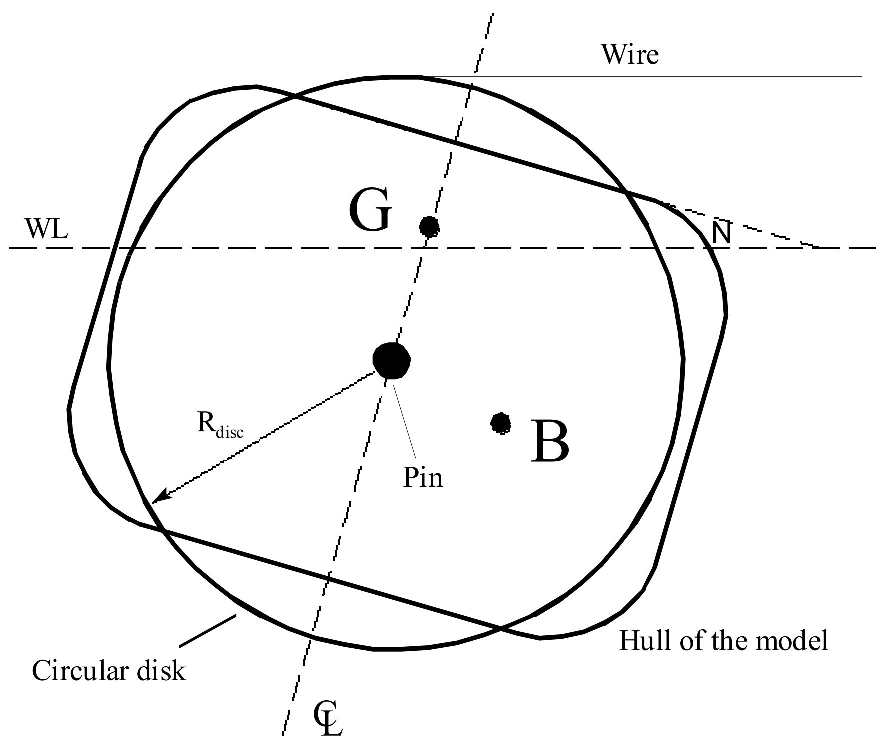


Figure 2 - Simplified View of Heeling Model

11. Re-arrange the equation at (11) to derive an equation that can be used to calculate the internal righting arm being developed by the model (GZ).

12. Using this apparatus and the equation above it will be possible to find the righting arm being developed by the 27-B-1 model at any angle of heel indicated on the protractor. The plot of righting arm, GZ against angle of heel is termed the curve of intact statical stability.

13. On the axis at Figure 3 plot the curve of intact statical stability **(starboard heels only)** for a ship with the following stability characteristics. **Ensure to label all axes.**

| | | | |
|---|---|---|---|
| a. | Range of stability | = | $0 - 88^{o}$ |
| b. | Angle of maximum righting arm | = | $50^{o}$ |
| c. | Maximum righting arm | = | 3.5 ft |
| d. | Righting arm at $30^{o}$ of heel | = | 2.0 ft |

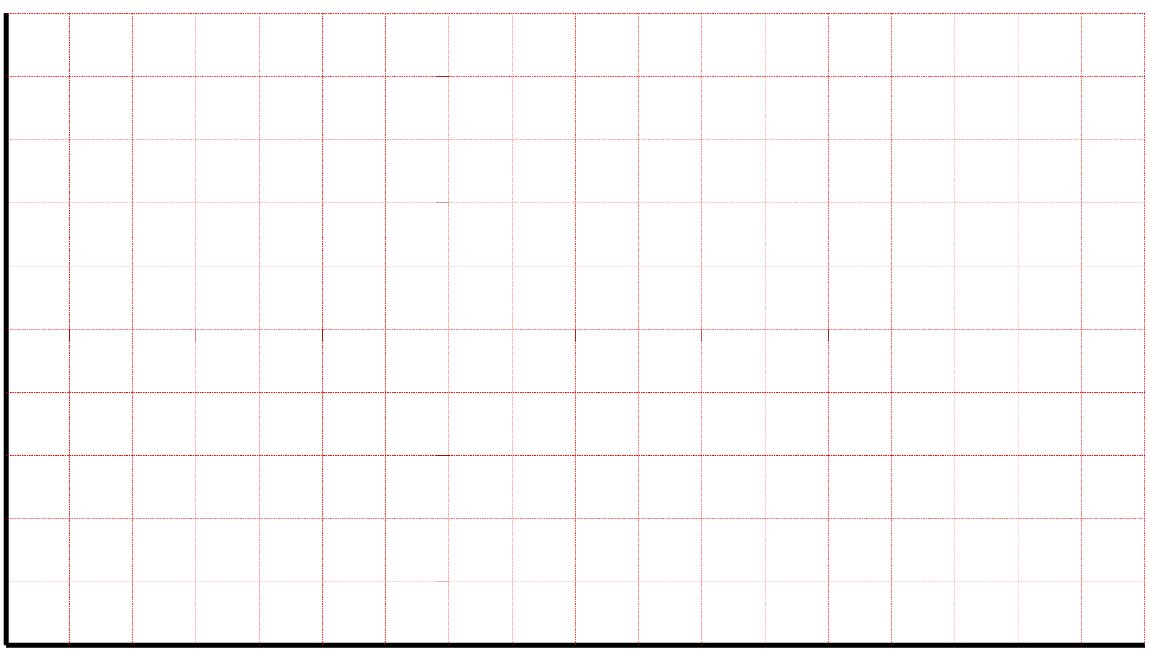

Figure 3 - Axis for Plotting Curve of Intact Statical Stability

14. When creating this curve for a full scale ship, it is not possible to rig apparatus such as that described earlier.

    How is the curve of intact statical stability produced for a full scale ship?

    ______________________________________________________________________

    ______________________________________________________________________

15. In the next part of this lab, the center of gravity of the ship will be raised thereby increasing KG. The effect this has upon the curve of intact statical stability will be measured. It should be possible to predict this effect by an analysis of the heeling ship shown diagrammatically at Figure 4.

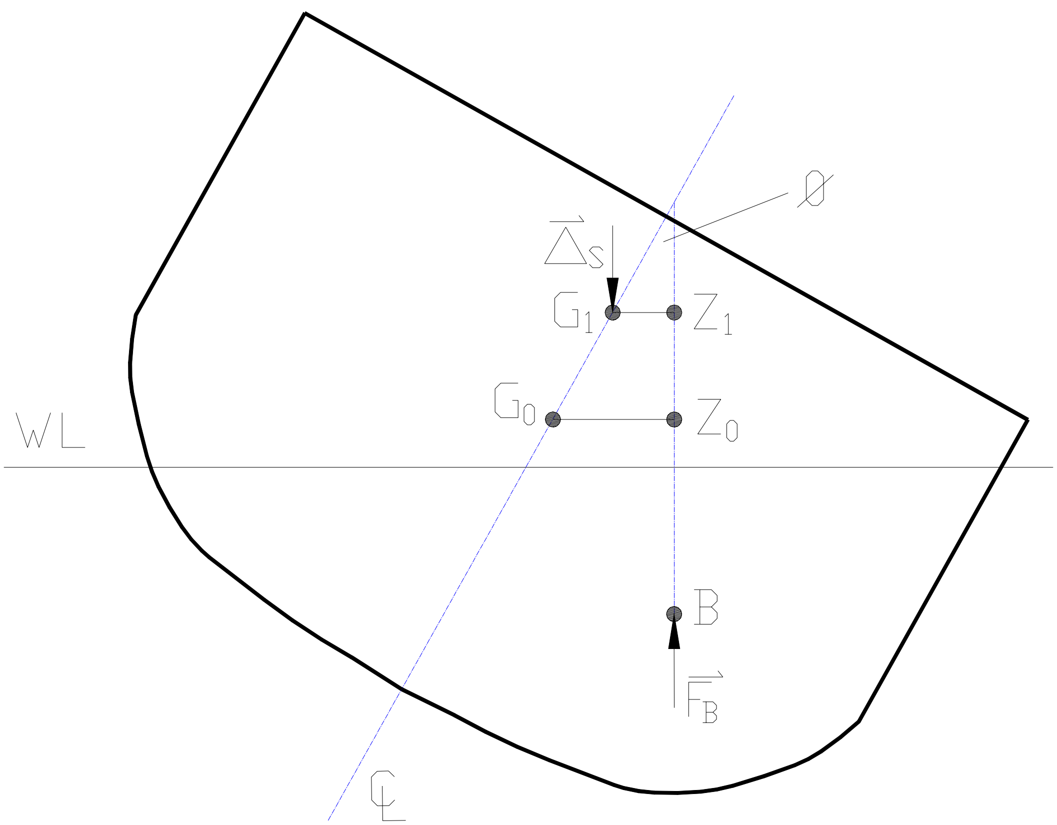


Figure 4 - The Heeling Ship with a Vertical Shift in the Center of Gravity

16. In the box below, use Figure 4 to derive an equation for the new righting arm ($G_1Z_1$) after a vertical shift in the center of gravity from $G_0$ to $G_1$. Your equation should include the old righting arm ($G_0Z_0$) and the angle of heel ($\phi$).

17. From your answer above, what effect do you believe an increase in the distance KG will have upon the stability of a ship? ______________________________________________

______________________________________________________________________

18. In the next portion of the lab, the center of gravity of the ship will be shifted transversely. The effect this has upon the curve of intact statical stability will be measured. It should be possible to predict this effect by an analysis of the heeling ship shown in Figure 3.

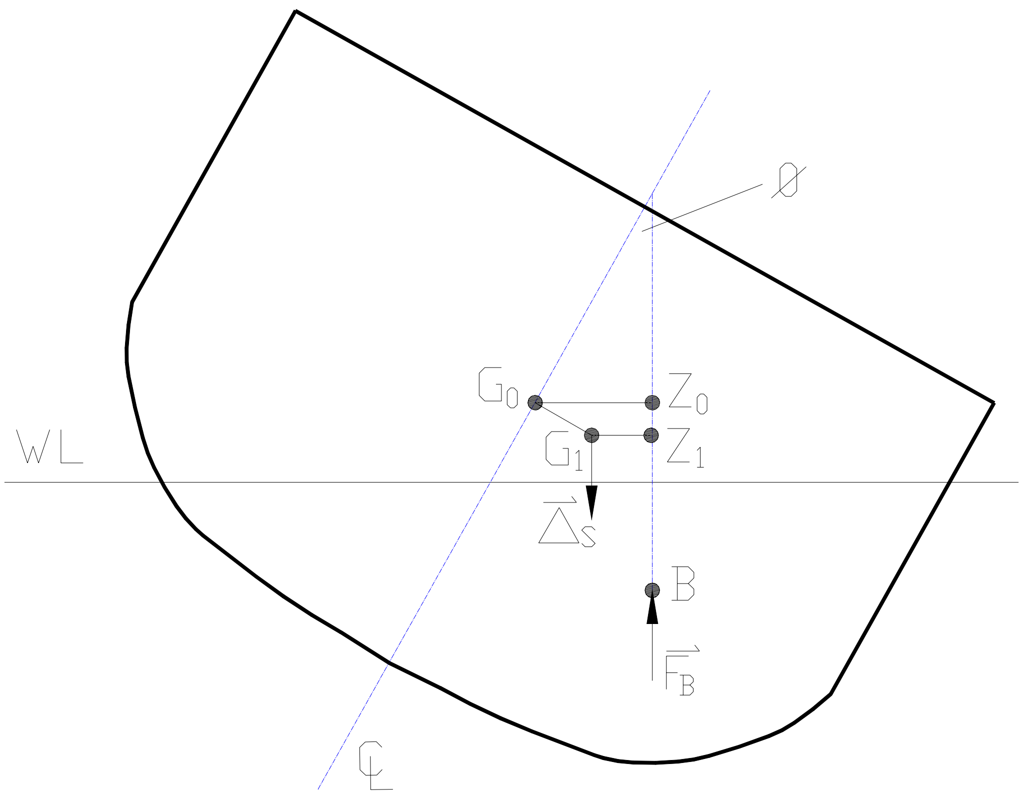


Figure 5 – The Heeling Ship with a Transverse Shift in the Center of Gravity

19. In the box below, use Figure 3 to derive an equation for the new righting arm ($G_1Z_1$) after a transverse shift in the center of gravity from $G_0$ to $G_1$. Your equation should include the old righting arm ($G_0Z_0$) and the angle of heel ($\phi$).

# IMPORTANT!!

20. *Before you can start the lab, you will need the information you acquired from the Inclining Experiment (Lab 4) concerning the 27-B-1 model you are working with.*

***Remember you must use the same 27-B-1 model for all your EN200 laboratories***

**a. Find the $KG_{light}$ you calculated from Lab 4.**

**b. Insert this data in the appropriate cell of the table on page 12 of the lab.**

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# EN200

# LAB 5/6:
# RIGHTING ARM - VERTICAL AND TRANSVERSE SHIFTS IN G

Instructions

1. This lab is **conducted in the hydrolab** on the lab deck of Rickover Hall.

2. You will need to **bring this lab to the lab period**. You must also have recorded the $KG_{light}$ found in the Inclining Experiment lab in the appropriate cell of the table on p11.

3. The lab is to be performed in small groups of 2 or 3 but **each member of the lab group is to submit their own work**. You can ask questions and discuss the content of the lab, but the submitted work must be your own. The lab is designed to provide a valuable learning experience, **copying another persons work will destroy this goal and limit your understanding of the course**.

4. Another way the learning experience of the lab can be destroyed is by failing to **follow the stages of the lab consecutively**. The lab follows a logical thought pattern, jumping ahead without doing the intervening theory questions will limit your understanding.

5. **All work must be shown on your lab for proper credit**. This means that you must show generalized equations, substitution of numbers, units and final answers. Engineering is communication. Other people should be able to understand your work.

6. **This lab is to be submitted at the end of the lab period.**

**Student Information:**

Name:___________________________ Date:_____________________

1st Partner________________________ 2nd Partner____________________________

3rd Partner:_______________________ 4th Partner:___________________________

## Part 2: Procedure

**Apparatus**

1. Before beginning the experiment, ensure the 27-B-1 model number corresponds with the number on the solid floored tank, the protractor and the tank. **This must be the same as the model used in the Inclining Experiment - Lab 4**.

27-B-1 model number = ______________________

**Light-ship Condition**

2. The first step is to ensure the model 27-B-1 is in its light-ship condition. This is achieved by the following:

   a. Ensure all detachable weights are off the model (1.5 lb weight, 4 x 0.15 lb weights, and protractor device).

   b. Ensure there is no loose water within the central compartment.

   c. **Ensure the solid floored tank with its flooded side down is securely installed in the center compartment.**

3. Find the scale weight of the model in its light-ship condition ($\Delta_{light}$) and insert it in the table on page 11. **This value should be the same as recorded in the previous lab. $KG_{light}$ should have been inserted in the table already**.

**Normally Loaded Condition**

4. The model must then be loaded to achieve its normally loaded condition. All quantities concerning the model can then have the suffix 'normal' once it has been loaded. The load consists of the following.

   a. Protractor device.

   b. One 1.5 lb weight mounted on the center post.

   c. 4 x 0.15 lb weights mounted on top of the 1.5 lb weight on the center post.

5. Use the scale and the rule provided to complete the table of data on page 11 and load the model so that it is in its normally loaded condition.

**Hint: Recall it is much easier to reference your vertical measurements to the weatherdeck on the 27-B-1 model and then add the distance of the weatherdeck above the keel to find Kg values.**

Height of Weatherdeck above the keel = ____________________

| | | | | |
|---|---|---|---|---|
| Light-ship Condition | $\Delta_{light}$ (lb) | | $KG_{light}$ (in) | |
| Protractor Device | $W_{protractor}$ (lb) | | $Kg_{protractor}$ (in) | |
| 1.5 lb Weight | $W_{1.5}$ (lb) | | $Kg_{1.5}$ (in) | |
| 4 x 0.15 lb Weights | $W_{4\ x\ 0.15}$ (lb) | | $Kg_{4\ x\ 0.15}$ (in) | |
| Normally Loaded Condition | $\Delta_{normal}$ (lb) | | $KG_{normal}$ (in) | |

6. To complete the table a value for $KG_{normal}$ must be calculated. This should be straightforward as all the necessary data is in the table. Use the following steps.

   a. In the box below write an equation for a vertical movement of G due to a weight shift, removal or addition using the values in the table to find $KG_{normal}$.

   b. Substitute the values in the table and calculate $KG_{normal}$. Place the value in the table.

**Construction of the Curve of Intact Statical Stability for Normally Loaded 27-B-1 Model**

7. The construction of the curve of intact statical stability can now begin. Perform the following steps.

   a. Make sure all the weights and protractor are secure on the model. Also ensure the hatch cover is correctly fastened. You are going to capsize the model, you don't want water entering the central compartment.

   b. Float the model in its normally loaded condition so that its pins are inserted in the grooves on the tank.

   c. Connect the wire from the circular disc to the force gauge making sure it passes around the groove in the circumference of the plate.

   d. With the wire in a slack condition ($F_{wire}$ = 0 lb), make sure the model is floating upright. Alter the locations of the transverse weights to achieve this.

   e. Zero the force gauge and **ensure the red switch is in its central (neutral) position.**

8. You can now begin to heel the model.

   a. Record the force in the wire at a heeling angle of zero degrees.

   b. Heel the model using the crank connected to the force gauge.

   c. Record the force $F_{wire}$ at 5 degree increments and place it in the table on page 13.

   d. When you have heeled the boat to capsize in one direction, turn the boat around and heel it to capsize on the other. Ensure you record the capsize angle!

   e. When completing the data table, remember that **by convention, forces acting to port, port distances, and port heeling angles are negative**.

9. To calculate the righting arm, GZ at each angle of heel, you will recall that in the prelab you derived the following equation.

$$\overline{GZ}(in) = \frac{F_{wire}\,(lb)\,R_{disc}\,(in)}{\Delta_S\,(lb)}$$

In this particular case, $\Delta_S = \Delta_{normal}$ which was calculated on page 11.
$R_{disc}$ , the radius of the disc is 3 in.

| Port Measurements | | |
|---|---|---|
| Angle of Heel $\phi$ (Degrees) | Force in the Wire $F_{wire}$ (lb) | Righting Arm GZ (in) |
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| Starboard Measurements | | |
|---|---|---|
| Angle of Heel $\phi$ (Degrees) | Force in the Wire $F_{wire}$ (lb) | Righting Arm GZ (in) |
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10. Plot this data on the axis at Figure 5. It is recommended that you use a spreadsheet to manipulate data and construct your plots. You will use the righting arms in the normally loaded condition in future labs.

**Remember:**

**label your axis correctly**
**title your plot correctly**
**port measurements and angles are negative**

11. From the plot your plot at Figure 5, complete the following table.

| **Heeling to Port** | |
|---|---|
| Range of Stability | |
| Maximum Righting Arm | |
| Angle of Max RA | |

| **Heeling to Starboard** | |
|---|---|
| Range of Stability | |
| Maximum Righting Arm | |
| Angle of Max RA | |

12. Show your understanding of the heeling ship by sketching the ship at the 3 angles of heel below. On each sketch show the location of the centerline, G, B, Z (if applicable), the waterline, angle of heel, and displacement and buoyant force vectors.

$\phi$ = zero $\phi$ = Angle of Max RA $\phi$ = capsize angle

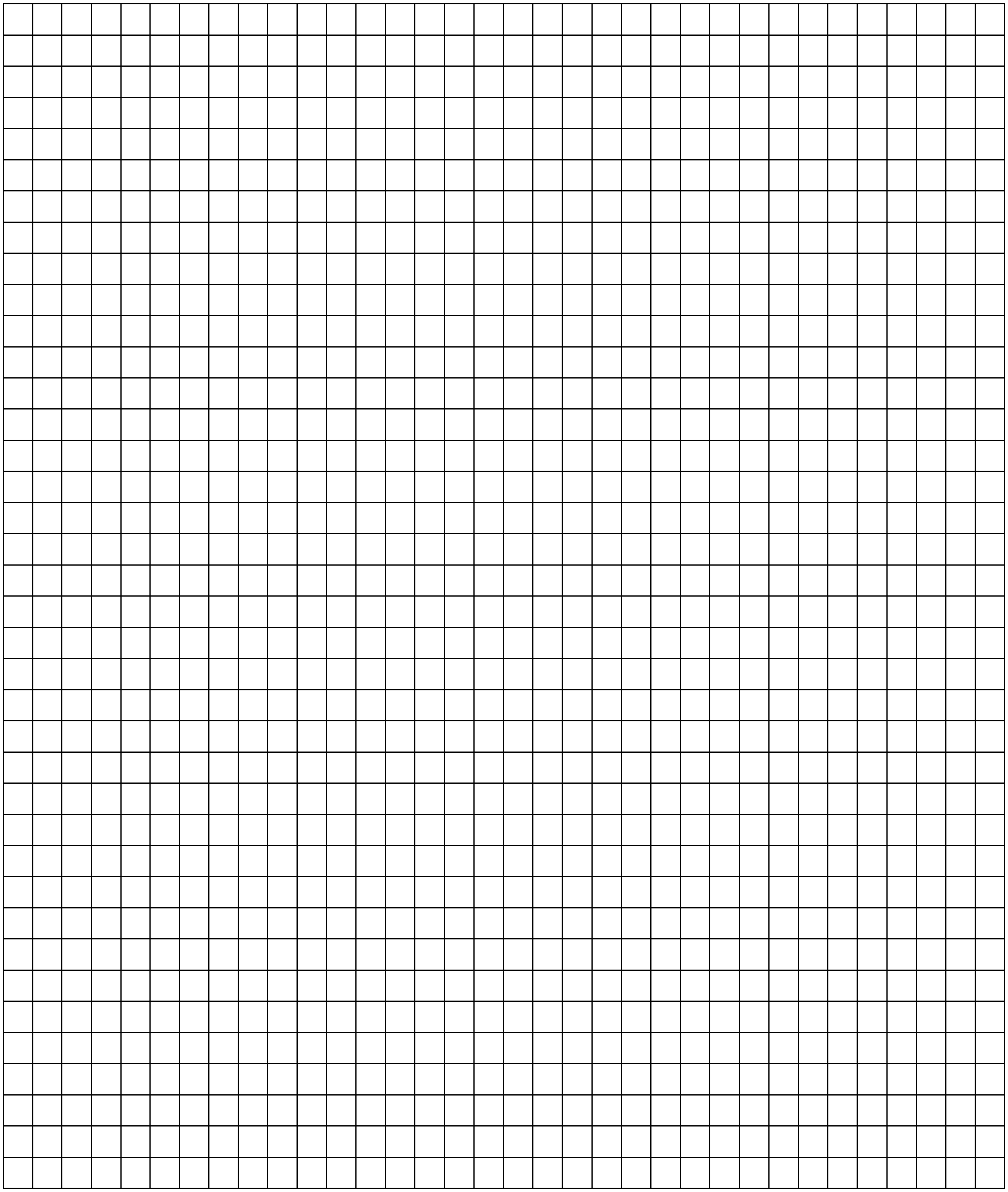

Figure 5 - Righting Arm Curve

## Righting Arm After Vertical Rise in G

13. The 27-B-1 model can be caused to have a vertical rise in G by inverting the solid floored tank within the central compartment. Invert the tank and re-assemble the model including all its weights. Make sure the hatch cover is securely clamped.

14. Now repeat the process you performed earlier to find the curve of intact statical stability. Use the table below to record the data. Remember, a ship at zero degrees heel does have a righting arm.

    **Do only starboard heels.**

| **Starboard Measurements** | | |
|---|---|---|
| Angle of Heel $\phi$ (Degrees) | Force in the Wire Fwire (lb) | Righting Arm GZ (in) |
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| **Starboard Measurements Continued** | | |
|---|---|---|
| Angle of Heel $\phi$ (Degrees) | Force in the Wire Fwire (lb) | Righting Arm GZ (in) |
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15. Plot the curve of intact statical stability for the ship in the inverted condition over on the same axis on page 15. Once again, you may use a spreadsheet program to plot this curve.

**Make sure you indicate which curve corresponds to which ship condition.**

16. Compare the curves of intact statical stability for the model in the 2 conditions: 'normally loaded' and 'inverted' by completing the table below.

| Starboard Heel Stability Criteria | | | | |
|---|---|---|---|---|
| **Normally Loaded Condition** | | | **Inverted Condition** | |
| Range of Stability | | | Range of Stability | |
| Maximum Righting Arm | | | Maximum Righting Arm | |
| Angle of Max RA | | | Angle of Max RA | |

17. In which condition is the model more stable? ___________________________________

Why? ___________________________________________________________________

18. What deduction can you make regarding the effect of an increase in KG on the stability of a ship?

_______________________________________________________________

**Calculation of the Effects of a Vertical Rise in G.**

19. The effects of a rise in G can be determined provided the amount it has moved is known. In this particular case you will recall that the rise in G was due to the inversion of the solid floored tank.

20. Use the box below to calculate the new KG of the model, call this value $KG_{inverted}$. To do this you will need the following information. $W_{tank}$ = 2.2 lb, $Kg_{tank}$ before the inversion was 3 inches, after the inversion it is 5 inches.

**Remember to show the generalized equation first, substitute your data and then calculate.**

21. In the prelab you proved that an increase in KG would reduce the righting arm (GZ) at an angle of heel ($\phi$) by the following equation.

$$\overline{G_1Z_1} = \overline{G_0Z_0} - \overline{G_0G_1}\,Sin\,\phi$$

Show that you understand the derivation of this equation by completing the diagram of the heeling ship at Figure 6. The diagram should include the center of buoyancy (B), the new and old centers of gravity ($G_0$ & $G_1$), the new and old righting arms ($G_0Z_0$ & $G_1Z_1$), the angle of heel ($\phi$), the displacement ($\Delta_S$)and the buoyant force ($F_B$).

**Also clearly show the sine correction term**.

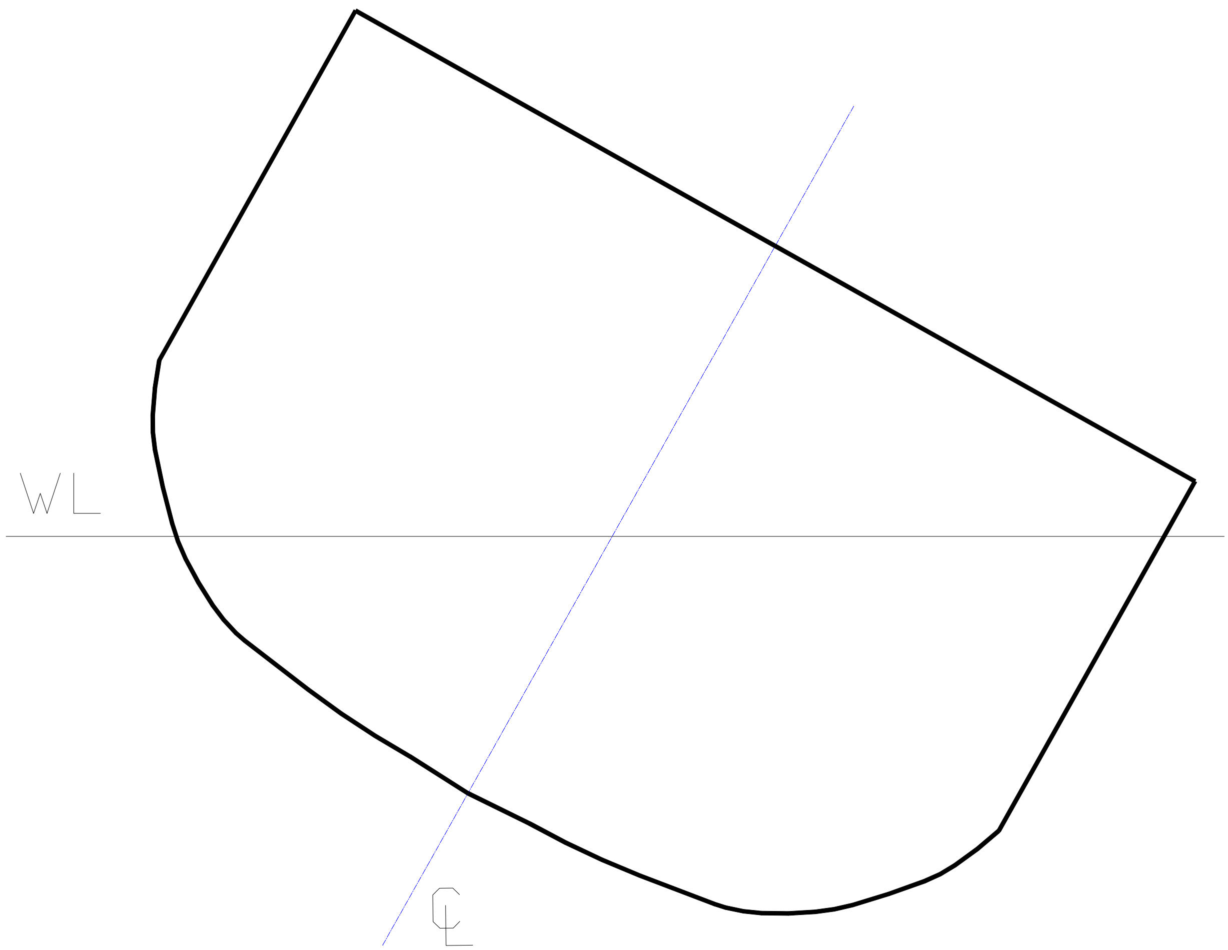


Figure 6 - The Heeling Ship with a Vertical Shift in G

22. Use the values for $KG_{normal}$ and $KG_{inverted}$ to calculate the magnitude of the line segment $G_0G_1$.

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23. Use this value and the sine correction equation to complete the table below.

| **Angle of Heel** $\phi$ **(Degrees)** | **Normally Loaded Righting Arm** $G_0Z_0$ **from Step 9 (in)** | **Sine Correction Term** $G_0G_1 \sin\phi$ **(in)** | **Calculated Inverted Righting Arm** $G_1Z_1$ **(in)** |
|---|---|---|---|
| 0 | | | |
| 15 | | | |
| 30 | | | |
| 45 | | | |

24. **Plot** the calculated data on the curve of intact statical stability at Figure 5. You may do this using a spreadsheet, or plot by hand. You do not need to connect these data points with a line.

25. Comment upon any differences between the calculated data points for the inverted righting arm with those found experimentally.__________________________________

______________________________________________________________________

______________________________________________________________________

26. Has this proved or disproved the accuracy of the sine correction? ____________________

Why? _________________________________________________________________

______________________________________________________________________

**Transversely Loaded Condition**.

27. Before the model can be moved to its transversely loaded condition, it must be floated in the tank and any initial list corrected with the transverse weights. Perform the following steps.

a. Return the internal tank to its original kg=3” configuration.

b. Make sure all the weights and protractor are secure on the model. Also ensure the hatch cover is correctly fastened. You are going to capsize the model, you don’t want water entering the central compartment.

c. Float the model in its normally loaded condition so that its pins are inserted in the grooves on the tank.

d Connect the wire from the circular disc to the force gauge making sure it passes around the groove in the circumference of the plate.

e. With the wire in a slack condition ($F_{wire}$ = 0 lb), make sure the model is floating upright. Alter the locations of the transverse weights to achieve this.

f. Zero the force gauge and make sure the red switch is in its central (neutral) position.

28. Now the model can be moved into its transversely loaded condition. Move the1.5 lb weight from the center post to the starboard post, leaving the 0.15 lb weights on the center post. All quantities concerning the model can then have the suffix ‘trans’ once these weights have been shifted.

29. Record the initial angle of list below. **Remember starboard angles are positive, port angles are negative.**

| | |
|---|---|
| Initial Angle of List (Degrees) | |

30. A quantity you will need in further calculation is the distance the weights have been shifted (t). This corresponds to the distance between the starboard and center posts. Record this distance below.

| | |
|---|---|
| Distance of transverse weight shift (inches) | |

**Construction of the Curve of Intact Statical Stability for Transversely Loaded 27-B-1 Model.**

31. The construction of the curve of intact statical stability can now begin. Perform the following steps.

    a. Record the angle of list corresponding to zero force in the wire.

    b. Heel the model using the crank connected to the force gauge.

    c. Record the force $F_{wire}$ at 5 degree increments and place the data in the table on page 11.

    d. When you have heeled the boat to capsize in one direction, turn the boat round and heel it to capsize on the other.

    e. When completing the data table, remember that **by convention, port distances and heels are negative.**

32. To calculate the righting arm, GZ at each angle of heel, you will recall that in the prelab you derived the following equation.

$$\overline{GZ}(in) = \frac{F_{wire}(lb)\,R_{disc}(in)}{\Delta_s(lb)}$$

Since there has been only a shift in weights on board the model, there has been no alteration in the models displacement. Consequently:

$$\Delta_S = \Delta_{normal} = \Delta_{trans}$$

You recorded $\Delta_{normal}$ at the bottom of page 8.

$R_{disc}$, the radius of the disc, is 3 in.

| Port Measurements | | |
|---|---|---|
| Angle of Heel $\phi$ (Degrees) | Force in the Wire $F_{wire}$ (lb) | Righting Arm GZ (in) |
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| Starboard Measurements | | |
|---|---|---|
| Angle of Heel $\phi$ (Degrees) | Force in the Wire $F_{wire}$ (lb) | Righting Arm GZ (in) |
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33. Plot this data on the axis on page 13, the curve of intact statical stability for the model in its normally loaded condition should be plotted already. You are encouraged to utilize the capabilities of a spreadsheet program to compute righting arms and plot data.

**Remember:**

**label your axis correctly**
**title your plot correctly**
**port measurements and angles are negative**

34. From the 2 curves on page 13, complete the following table.

| **Heeling to Port** | | |
|---|---|---|
| Condition | Normally Loaded | Transversely Loaded |
| Range of Stability (Degrees) | | |
| Maximum Righting Arm (in) | | |
| Angle of Max RA (Degrees) | | |

| **Heeling to Starboard** | | |
|---|---|---|
| Condition | Normally Loaded | Transversely Loaded |
| Range of Stability (Degrees) | | |
| Maximum Righting Arm (in) | | |
| Angle of Max RA (Degrees) | | |

35. What deduction can you make from the table about the overall stability of a ship when heeling in the direction of a transverse weight shift?______________________________

________________________________________________________________________

Why? ____________________________________________________________________

36. What deduction can you make from the table about the overall stability of a ship when heeling away from the direction of a transverse weight shift?________________________

________________________________________________________________________

Why? ____________________________________________________________________

37. To show you understand the geometry of the heeling conditions sketch the model in the following conditions and heeling angles. Your sketches should include the center of buoyancy (B), center of gravity (G), the displacement ($\Delta_{normal}$ or $\Delta_{trans}$), the buoyant force ($F_B$), the angle of heel ($\phi$), the waterline and the righting arm (GZ) if applicable.

| **Normally Loaded Condition** | **Transversely Loaded Condition** |
| --- | --- |
| Zero degrees of heel | Initial heeling angle |
| Angle of $GZ_{max}$ to starboard | Angle of $GZ_{max}$ to starboard |
| 60 degrees of heel to port | 60 degrees of heel to port |

| Normally Loaded Condition | | Transversely Loaded Condition |
|---|---|---|
| Capsize angle to port | | Capsize angle to starboard |

**Calculation of the Effects on Stability of a Transverse Shift in G.**

38. The effects on stability of a transverse shift in G can be determined provided the amount it has moved is known. In the box below, give the generalized equation for the calculation of a new TCG after a weight shift, addition or removal.

In this particular case you will recall that the movement in G was created by the shift of the 1.5 lb weight ($W_{1.5}$) from the center post to the starboard post, a distance (t). This distance was recorded on page 9.

Rewrite the equation above in terms of these quantities, substitute their values and solve for the TCG of the model in its transversely loaded condition ($TCG_{trans}$).
**Hint: $TCG_{normal}$ can be assumed zero as the model had zero initial list in its normally loaded condition.**

39. In the prelab you proved that a transverse shift in G would reduce the righting arm (GZ) at an angle of heel (ϕ) by the following equation.

$$\overline{G_1Z_1} = \overline{G_0Z_0} - \overline{G_0G_1}\ Cos\,\phi$$

Show that you understand the derivation of this equation by completing the diagram of the heeling ship at Figure 6. The diagram should include the center of buoyancy (B), the new and old centers of gravity ($G_0$ & $G_1$), the new and old righting arms ($G_0Z_0$ & $G_1Z_1$), the angle of heel (ϕ), the displacement ($\Delta_S$) and the buoyant force ($F_B$).

**Also clearly show the cosine correction term.**

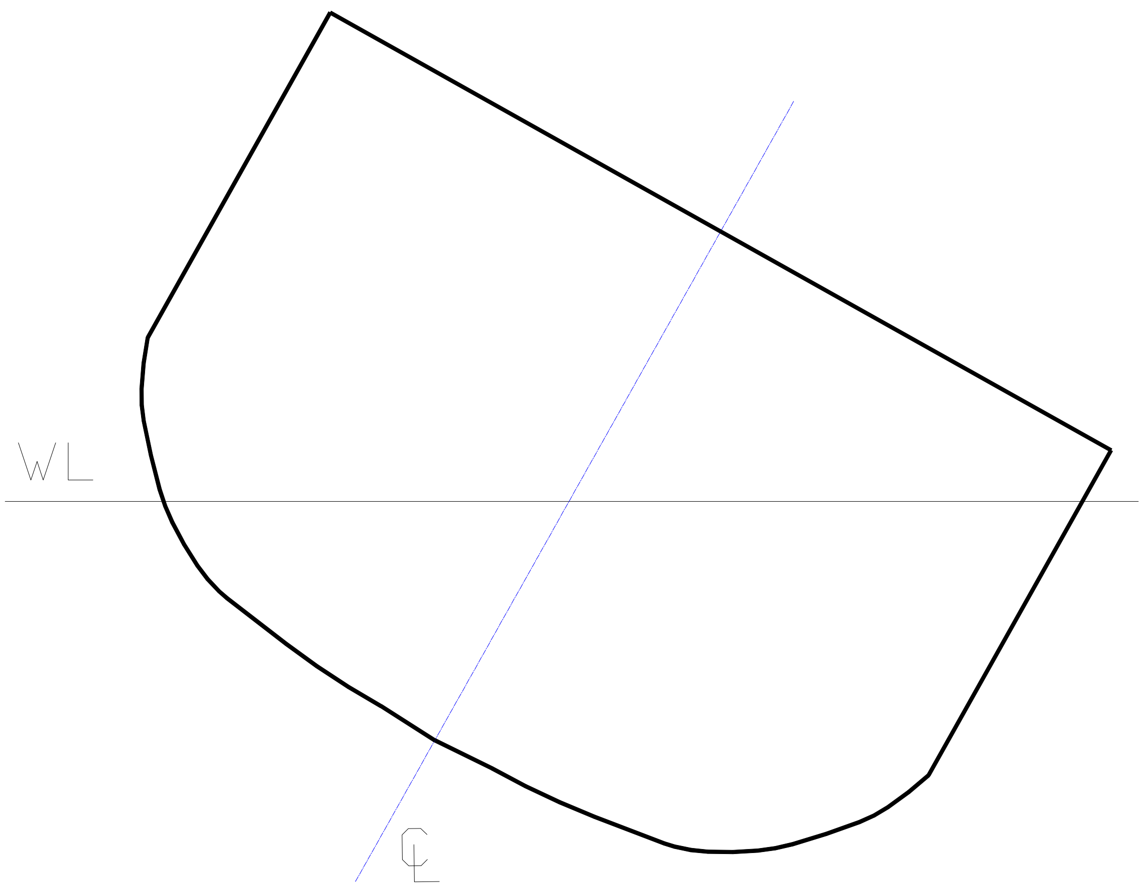


Figure 4 – The Heeling Ship with a Transverse Shift in G

40. Use the values for $TCG_{normal}$ and $TCG_{trans}$ to calculate the magnitude of the line segment $G_0G_1$.

| |
|---|
| |

41. Use this value and the cosine correction equation to complete the table below.

| **Angle of Heel $\phi$ (Degrees)** | **Normally Loaded Righting Arm $G_0Z_0$ (in)** | **Cosine Correction Term $G_0G_1\cos\varphi$ (in)** | **Calculated Corrected Righting Arm $G_1Z_1$ (in)** |
|---|---|---|---|
| 0 | | | |
| 15 | | | |
| 30 | | | |
| 45 | | | |

42. Plot the calculated data on the curve of intact statical stability on page 13.

43. Comment upon any differences between the calculated data points for the corrected righting arm with those found experimentally. ___________________________________

_____________________________________________________________________________

_____________________________________________________________________________

44. Has this proved or disproved the accuracy of the cosine correction? __________________

Why? ______________________________________________________________________

_____________________________________________________________________________